



THERMO-MECHANICAL FATIGUE CRACK GROWTH IN ADVANCED AEROSPACE ALLOYS

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This project has received funding from the European Union's Horizon 2020 research and innovation programme and Joint Undertaking Clean Sky 2 under grant agreement No 686600



Prifysgol Abertawe Swansea University



Introduction



Swansea University Bay Campus



DevTMF. This project has received funding from the *European Union's Horizon 2020 research and innovation programme* and Joint Undertaking Clean Sky 2 under grant agreement No 686600.



DevTMF Partners



Swansea University, Wales. *Testing and analysis*

Nottingham University, England. Modelling and round robin testing Linkoping University, Sweden. Modelling and round robin testing Rolls-Royce plc, UK.

Material and technical support

Introduction



- Swansea University Background in TMF
- TMF total life testing
- TMFCG Test Development
- Crack tip heating investigations
- TMFCG Test Results
- Phase angle effects
- Damage mechanisms



Background in TMF



Strain Control - Induction

Non Metallic – Lamp Furnace

Fatigue Crack Propagation – Induction



Pyrometer

ean

D

Dev



Thermography



Thermocouple

- ASTM E2368-10. Strain Controlled TMF Testing, 2010.
- ISO 12111:2011. Strain-controlled TMF Testing, 2011.
- BAM. CoP Force-Controlled TMF Testing, 2015.

Industrial Motivation



- Increased turbine entry temperatures
- Thinner disc rims and advanced cooling systems leading to larger thermal gradients
- Complex loading regimes within the gas turbine leading to diverse phasing between temperature and strain
- Extrapolation of isothermal fatigue (IF) results to incorporate these effects show limited success
- Generation of TMF data is required to allow the development of lifing methodologies under <u>TMF</u> loading



Thermo-Mechanical Fatigue (TMF)



Diverse mechanisms are involved, Primarily . . .

Fatigue Creep Oxidation

- > TMF loading can be more damaging than isothermal fatigue at an equivalent T_{max}
- Complex interaction within diverse phase angles between peak temperature and strain range



Effect of peak temperature



- > At 750°C OP data shows a significant decrease in TMF life.
- Likely to be due to increased oxidation effects

TMF lives consistently shorter than isothermal fatigue lives.

Crack propagation





For fatigue lives that are less than 5000 cycles it is not appropriate to consider only crack initiation as the dominant factor in fatigue life.

TMFCG Test Development





Crack Tip Heating Investigations





Waspaloy crack length vs. number of cycles: furnace and induction coil comparisons at 650°C, 450MPa and R=0.1.

Ti6246 with crack plane at 500°C. Profile indicates no effect of crack tip heating.



Fine and Coarse grained RR1000



Fine grained RR1000



Coarse grained RR1000



Image courtesy of Li et al, Effects of microstructure on high temperature dwell fatigue crack growth in a coarse grain PM nickel based superalloy, Acta Materialia, Volume 90, 15 May 2015, Pages 355-369

Effect of Lamp Furnace vs Induction Coil





Fine Grained RR1000 TMF CP



TMF Data 300-700°C





Strong dependence on phase angle

Rates tend to approximate temperature at which peak stress occurs

Coarse Grained RR1000 TMF CP



TMF Data 400-750°C



Oxidation damage





Effects of Peak Temperature





- TMF CG RR1000
- In phase tests show faster
 rates than equivalent
 isothermal tests
- Dependent on cycle time
- In Out of Phase tests
 - increased Tmax influencing
 - TMF CP rates

da/dN [m/cycle]

Mechanisms of crack growth in OP tests



- Transgranular failure indicates minimal effect of oxidation
- Acceleration with increased peak temperature must be due to alternative mechanism
- Compressive stresses at crack tip relieved during high temperature portion of cycle?
- Increased temperature increased relaxation
- More relaxation leads to greater tensile strain and higher increment of crack growth?





Fatigue Damage XII, Hyannis, September 2018

500 10.0k∨ 5.6mm x1.00k SE

Fine Grained RR1000 TMF CP



TMF Data 300-700°C





Strong dependence on phase angle

Rates tend to approximate temperature at which peak stress occurs



Results: 90° OOP CW vs. ACW theory

> CW:

- Unloaded at high temperatures which oxidises crack tip because there is no crack growth so oxides reach a few grains beyond tip
- Loads the oxidised crack tip so crack grows along oxidised grain boundaries causing more of an intergranular failure

> ACW:

- Unloaded at low temperatures so there is no/less oxidation
- Loaded at higher temperatures so creating new surfaces and preventing oxidation of crack tip causing dynamic transgranular failure i.e. Crack growth faster than oxidation process

> Theory to the test:

- 500 second cycle TMF OOP90° ACW test to manipulate mechanism
- Check if oxidation surpasses crack growth rate for intergranular failure



Results: 90° OOP ACW (80s) Crack Progression





ROLLS ROYCE

Results: 90° OOP ACW (500s) Crack Progression





Results: Evidence of Crack Tip Blunting



- It is clear that the longer cycle results in a wider crack throughout the test
- Flat gradient of the Paris curve supports this crack tip blunting theory



- The crack growth is retarded by the reduced stress concentration at the crack tip
- Is this due to oxidation layers on the upper and lower surfaces of the crack?



CW and ACW Diamond 90 cycles



- Accelerated crack growth in ACW 90 cycles
- Slow crack growth in CW 90 cycles
- Often a low gradient is seen early in the test (oxidation dominated) giving way to an increased gradient as dynamic failure takes over



ΔK [MN-3/2]







- Crack propagation techniques are developing towards a Code of Practice to enable damage tolerant lifing approaches.
- Significant differences in TMF cycles due to phase angle occur in both fine grain and coarse grain material
- In phase tests dominated by oxidation damage
- Out of phase tests influenced by stress relaxation of compressive stresses around the crack tip. Higher temperatures promote more relaxation which leads to a greater increment of crack growth.
- CW and ACW cycles can be very sensitive to oxidation and rates may depend on cycle times.







Acknowledgements

This project has received funding from the European Union's Horizon 2020 research and innovation programme and Joint Undertaking Clean Sky 2 under grant agreement No 686600.

The provision of materials and technical support from Rolls-Royce plc is gratefully acknowledged. A special mention must be paid to Turan Dirlik, Steve Brookes, Veronica Gray and the ISM/SMaRT staff and Jennie Palmer.

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Dirlik Controls Software for Materials and Component Testing

Forced Air Cooling





Localised/Focused Cooling

Rolls

lean

Basic Fan Cooling



Diffuse uniform cooling through air amplifiers



Induction Coil Designs





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Pre-Crack Procedure





Rolls

Thermo-Mechanical Fatigue Crack Growth Pre-Cracking

Stage	Temperature (°C)	Waveform	Frequency (Hz)	Stress (MPa)	Duration (µv)
1	Ambient	Sine	5	600	25
2	Ambient	Sine	5	500	50
3	Ambient	Sine	1	500	75

